NASA CR-114281
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STUDY OF AEROSPACE STRUCTURAL MANUFACTURING CONCEPTS

VOLUME 1 OF 3

SUMMARY

15 MARCH 1971

PREPARED FOR:

National Aeronautics and Space Administration
Office of Advanced Research and Technology
Contract NAS2-5857

BY

APOLLO SYSTEMS • SPACE DIVISION
GENERAL ELECTRIC COMPANY
DAYTONA BEACH, FLORIDA

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FOREWORD

This is the final report of a three-phase study of Aerospace Structural Manufacturing Concepts including investigations of the economic impact of changes in manufacturing technologies and other factors, i.e., quantity, rate, design improvements, etc. The study was performed for the National Aeronautics and Space Administration under Contract NAS2-5857, monitored by Mr. Kenji Nishioka and Mr. Harry Hornby of the Advanced Concepts and Missions Division of the Office of Advanced Research and Technology.

This investigation was broad in scope and used data from the primary sources summarized in Table 1 and from the numerous references listed at the end of Volumes 2 and 3. Acknowledgement is extended to the many people in these Government, university and aerospace contracting agencies who provided much valuable information for this study.

Table 1

Sources of Manufacturing Information

Area of Investigation	Primary Sources of Data for This Study
Pre-Manufacturing Technologies	MSFC, Grumman, North American Rockwell, McDonnell Douglas Astronautics Co., GE/RESD, GE/AS
Manufacturing Technologies • Metal Removal • Metal Forming • Assembly & Other	MSFC, Air Force Manufacturing Lab, Battelle, Grumman, North American Rockwell; GE/RESD, GE/AS, GE/Jet Engine, GE/Manufacturing Services; McDonnell Douglas Astronautics Co., plus 26 Subcontractors
Quality Control & Test Technologies	MSFC, GE/RESD, GE/AS, North American Rockwell, McDonnell Douglas Astronautics Co., Grumman
Factors Affecting Manufacturing	MSFC, GE/RESD, GE/AS, Grumman, North American Rockwell, Air Force Manufacturing Lab, Univ. of Florida (Dr. Burns), Battelle, GE/Manufacturing Services, McDonnell Douglas Astronautics Co.
Plant Facilities	MSFC, GE/RESD, GE/AS, Grumman, North American Rockwell, GE/Manufacturing Services, McDonnell Douglas Astronautics Co., Grumman

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SUMMARY

This is Volume 1 of the three-volume series of the final report summarizing the results of a Study of Aerospace Manufacturing Concepts. The numerous manufacturing factors and technologies are identified and discussed in Volume 3. Impact of these factors and technologies on structural manufacturing costs are evaluated in Volume 2 for two representative structures: (1) a nonpressurized support frustum similar to that used on the Mark XII launch vehicle, and (2) a typical liquid propellant pressurized tank. Detailed manufacturing line definitions are established for two production rates (2 per year and 20 per year) for each of three manufacturing lines spanning state-of-the-art and improved and advanced manufacturing technologies. A computerized simulation model (MANCAN) was used for accumulating costs for assessing the impact of variations and interactions of factors on manufacturing cost.

Cost distributions for the nominal cases, illustrated in Figure 1, show the predominant importance of facilities and tooling on manufacturing costs. Facilities and tooling costs ranged from 42 percent to 81.2 percent of the total, far outshadowing recurring costs such as materials and labor. Improved manufacturing technologies have only a limited impact on costs. Thus, the largest potential area for cost reductions lies in those factors which reduce facility and tooling expense—such as assumptions of depreciation, taxes, and interest. For the low production rate of current space programs, even if the labor and material were free, the total costs would be reduced by only a modest amount.

The impact of the facility and tooling costs on the unit production costs are illustrated in Figure 2, showing the marked decrease if these costs are written off against increased quantity. The vertical spread of these areas illustrates the range of costs identified in this study with changes in program factors. Coupling high quantity production with advantageous factors reduces unit production costs by approximately two orders of magnitude. This is the order of cost reductions sought for future aerospace vehicles, such as the space station and space shuttle. Therefore, technology developments aimed at reducing future aerospace structural manufacturing costs can be focused best on simple, rugged structures that can be produced in quantity in inexpensive facilities. The weight and performance penalties, incumbent with such designs may well be corrected through use of advanced materials—a productive area for future study.

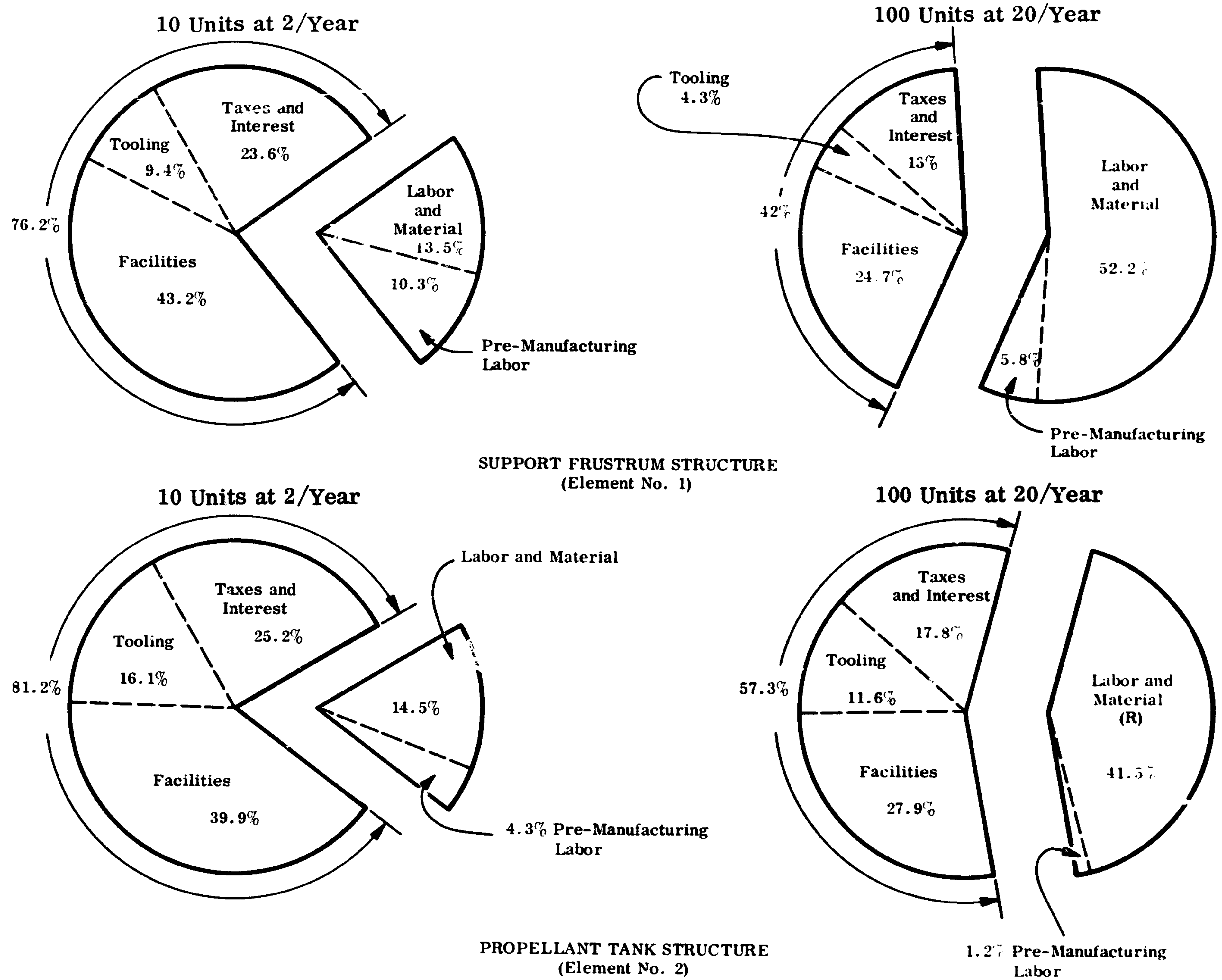


Figure 1. Structural Manufacturing Cost Distributions

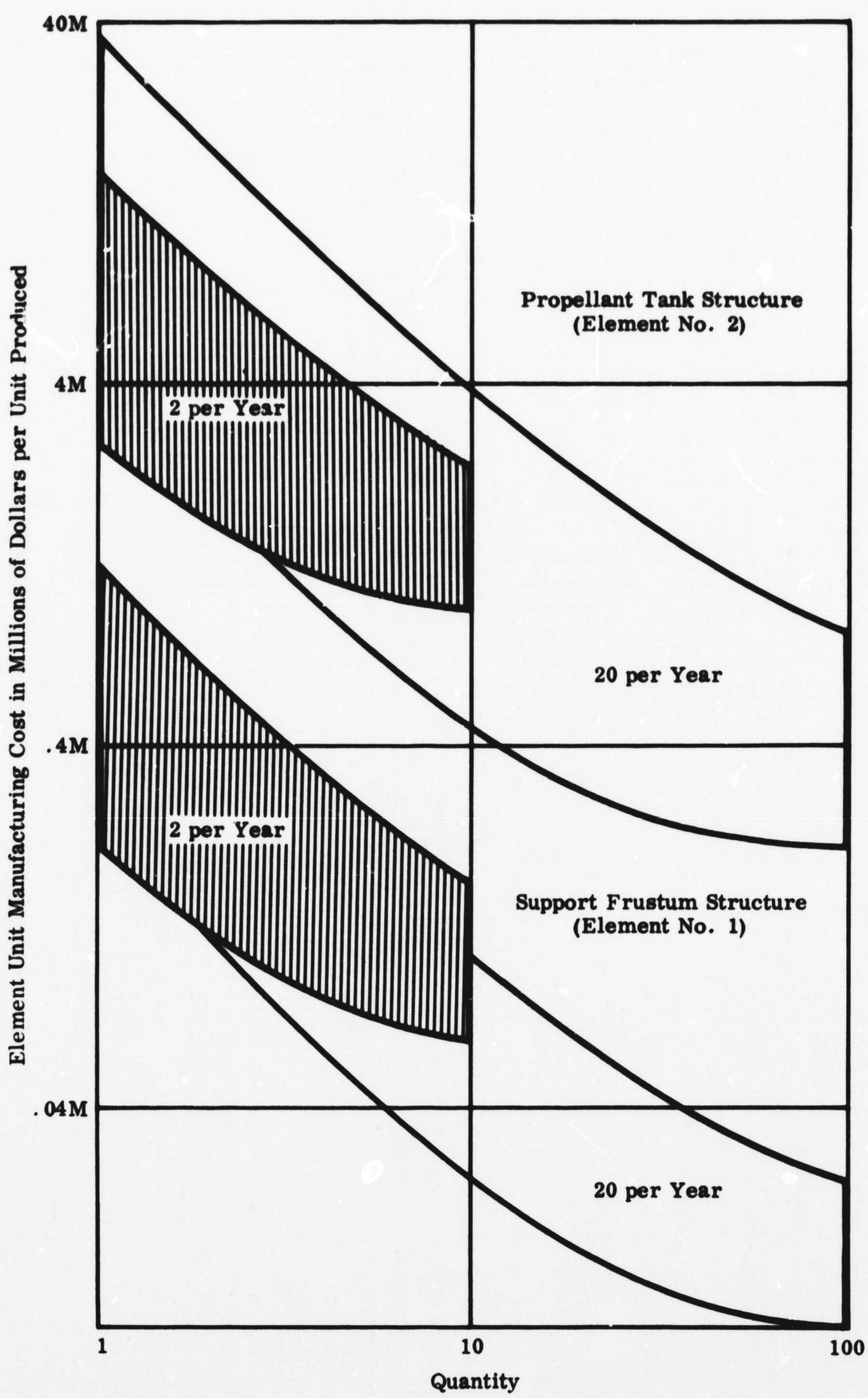


Figure 2. Range of Unit Manufacturing Costs (Manufacturing Program Length—5 Years)

SECTION 1

INTRODUCTION

Previous studies have shown that significant reductions in structural weight can be achieved with the use of advanced materials in future large launch vehicles. The General Electric Company, under contract NAS2-3811[1], has shown that structural weight reductions of 60 to 70 percent can be realized in large launch vehicles with the substitution of materials, such as beryllium or boron/epoxy honeycomb for the conventional aluminum integrally stiffened skin construction. Trade-offs against recurring cost were noted in a second study by General Electric under contract NAS2-5047[3]. These potential weight reductions will significantly improve launch vehicle performance. In these studies, technological areas of interest for future large launch vehicles were evaluated parametrically for technical feasibility and economic characteristics.

This study is essentially a continuation of the above studies and is a broad investigation of the manufacturing technology of aluminum aerospace structural systems to identify the significant manufacturing factors influencing overall structural system manufacturing cost. Results from this study will help to provide a manufacturing system cost baseline and cost analyses tools and techniques along with the identification of potential areas for cost reduction.

This baseline will serve as the foundation upon which to develop cost indices and reductions for future aerospace programs utilizing advanced materials and related manufacturing technologies.

Other studies presently in progress and/or completed for the NASA Office of Advanced Research and Technology complement this study. Boeing Aircraft performed a detailed cost study of large launch vehicles which provides a range of payload capability under Contract NAS2-5056, "Cost Studies of Multipurpose Large Launch Vehicles." McDonnell-Douglas Aircraft Corporation developed a cost model and performed cost studies of spacecraft under Contract NAS2-5022, "Study of Optimized Cost/Performance Design Methodology for Orbital Transportation Systems." North American-Rockwell

[1] Superscripts refer to Reference in Section 5.

has studied the costs of a spectrum of launch vehicles from performance and cost viewpoints under Contract NAS7-368, "Influence of Structure and Material Research on Advanced Launch Systems' Weight, Performance and Cost."

The successful achievement of larger launch vehicles, such as Saturn IB, Saturn V, and Titan III, has not brought the expected reduction in costs of delivering payload-to-orbit. Instead, these multi-billion dollar launch vehicle developments have produced launch vehicles of unprecedented success and reliability. The importance of achieving safe and successful flights has dominated the development cycle.

All systems of the launch vehicles should be designed on an optimized cost/performance basis in order to achieve desired lower costs of vehicles. The structures manufacturing area was chosen for this study to explore potential manufacturing cost reductions since it represents a large portion of the launch vehicle costs and a wealth of background data could be assembled for evaluation.

The primary impact of manufacturing systems cost reduction will be a step in the direction to foster and promote more space programs per dollar spent.

SECTION 2

STUDY APPROACH

2.1 INTRODUCTION

This study was accomplished in three phases as summarized in Table 2-1 and illustrated in Figure 2-1.

Table 2-1

Study Approach

Phase I—Survey of Manufacturing Techniques and Factors

a. Selection of areas to be surveyed.

b. Survey of the selected areas.

c. Evaluation of survey data and identification of cost impacting factors.

d. Selection of specific structural elements and manufacturing technologies for Phase II study.

Phase II—Representative Manufacturing Lines and Model Description

a. Selection and detailed development of manufacturing computer model.

b. Identification of manufacturing lines and potential areas for improvement.

c. Identified Phase III plans to determine sensitivity of manufacturing cost, to changes in system factors (developed in Phase I), and to the interaction of two or more system factors concurrently impacting the manufacturing system.

Phase III—Manufacturing System Analyses

a. The impact of manufacturing technology differences and changes in factors upon manufacturing cost.

b. Interaction analyses of several changes in factors varied concurrently and their impact on the manufacturing cost.

2.2 STRUCTURAL ELEMENTS SELECTED FOR DETAILED STUDY

At the conclusion of Phase I, two representative structural elements were selected for detailed study in Phase II and III. These structural elements were selected because current manufacturing technologies and related cost could be established for the predetermined production rates of 2 and 20 per year for a total program of up to five years in length.

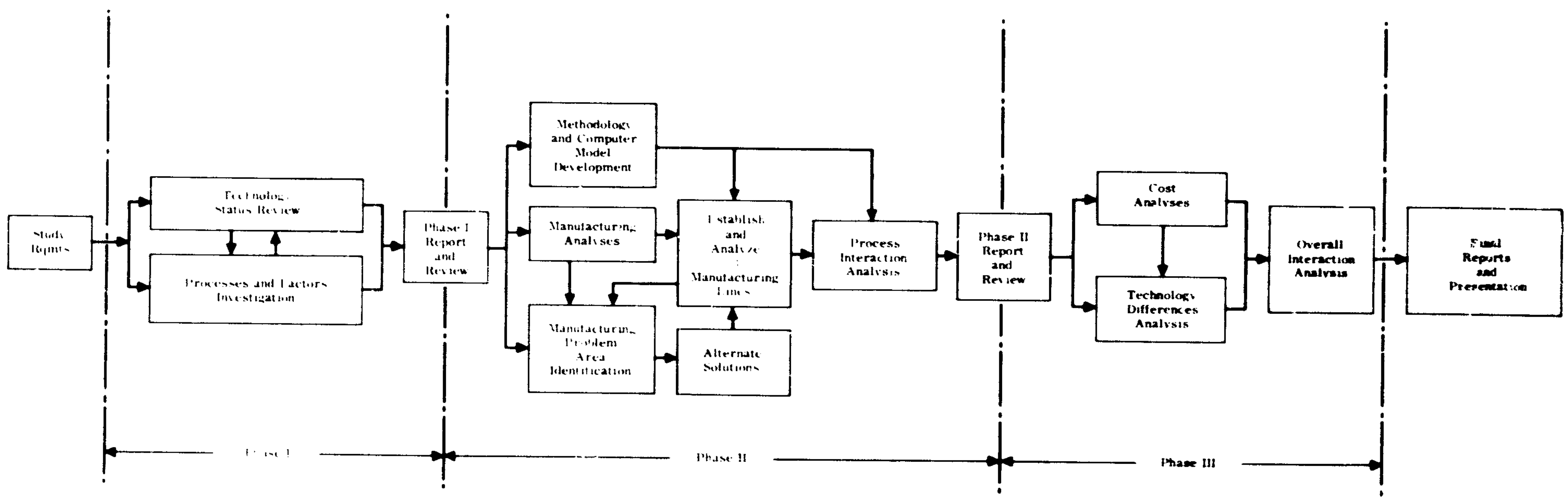


Figure 2-1. Overall Study Work Flow

The first structural element selected, shown in Figure 2-2, is a Support Frustum similar to the Mark XII frustum manufactured by the General Electric Company.

The second structural element selected, shown in Figure 2-3, was a large propellant tank such as used in a stage of the Saturn V launch vehicle. This tank is generic and the design dimensions were established for a tank 21.6 feet in diameter and 56.6 feet long. A generic type of structure was selected rather than an actual structure to facilitate objectivity in the manufacturing analysis and to avoid undue reflection on any particular launch vehicle tankage already developed.

For each of the above structures, state-of-the-art manufacturing lines, including facilities, tooling, fabrication and assembly processes, labor requirements, and related costs were established for production rates of 2 and 20 per year. Actual data supplied by the General Electric Company, Space Division, for Structural Element No. 1, were adjusted for the selected production rates used in developing the state-of-the-art line. Facilities, tooling, fabrication, and assembly processes for the state-of-the-art line for Structural Element No. 2 are a composite of those used throughout the aerospace industry for such structures, as determined from the survey trips. Related cost data were developed by the General Electric Company cost estimating personnel based upon experience, discussions with tooling manufacturers, and appropriate related data.

With the state-of-the-art line, as a base, the computer manufacturing model illustrated in Figure 2-4 was used to identify and analyze the problem areas, and the solutions obtained were placed in one of the following three categories:

a. Solutions Readily Available.
b. Solutions Requiring Technology Development.
c. Solutions Requiring Major Technology Development.

Changes to the state-of-the-art lines (Line 1) brought about by (a) solutions formed the base of the improved lines (Line 2), and change to the improved lines brought about by solutions (b) and (c) were instrumental in forming the advanced lines (Line 3).

2.3 STUDY VARIABLES

With the aid of the manufacturing models of these lines, illustrated in Figure 2-4, studies were made of the impact on cost of selected program factors from the spectrum listed in Figure 2-5 and discussed in detail in Volume 3. These selected program factors, together with variables such as structure type, manufacturing line, quantity, costing elements,

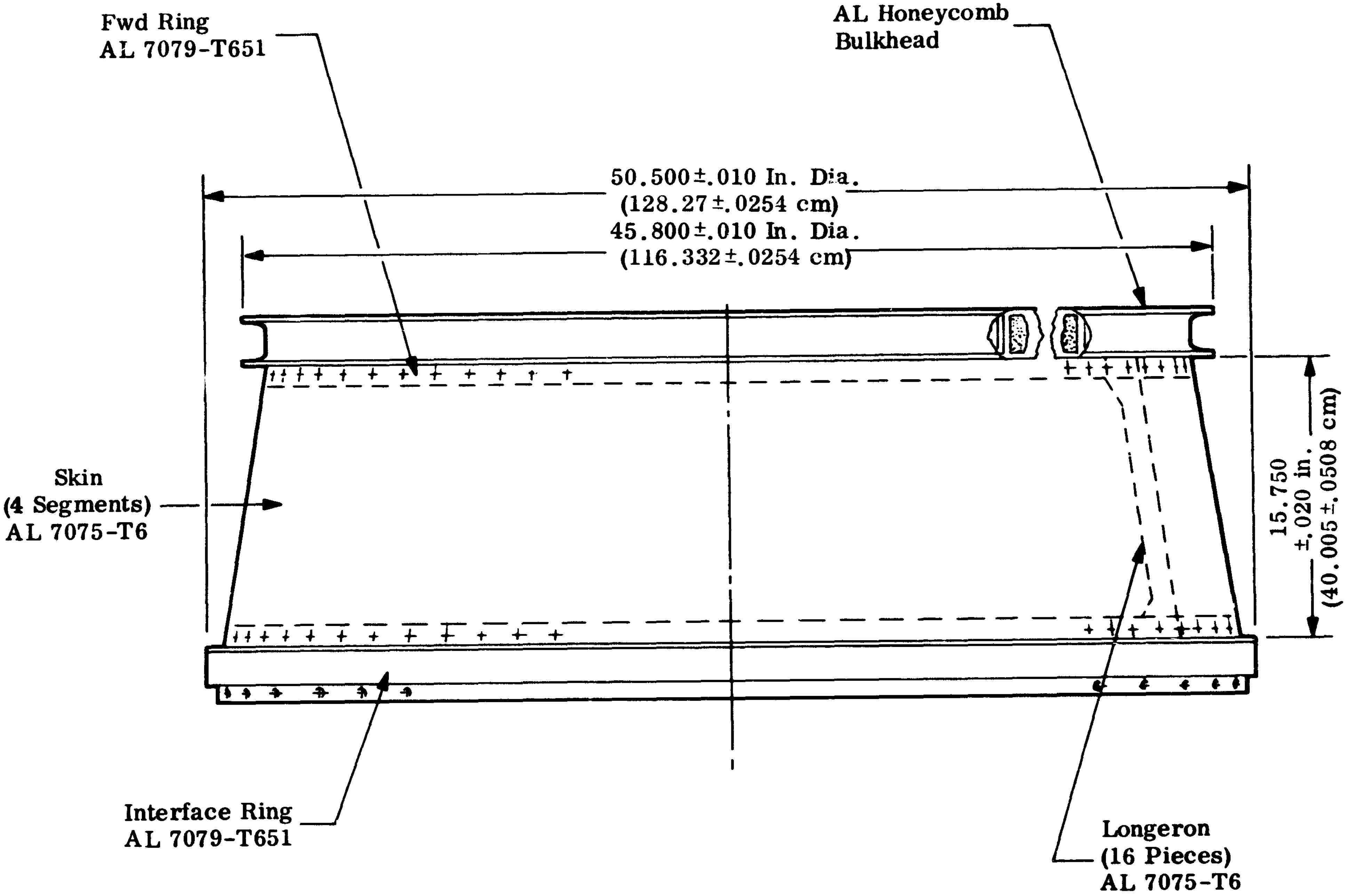


Figure 2-2. Support Frustum Structure (Structural Element No. 1)

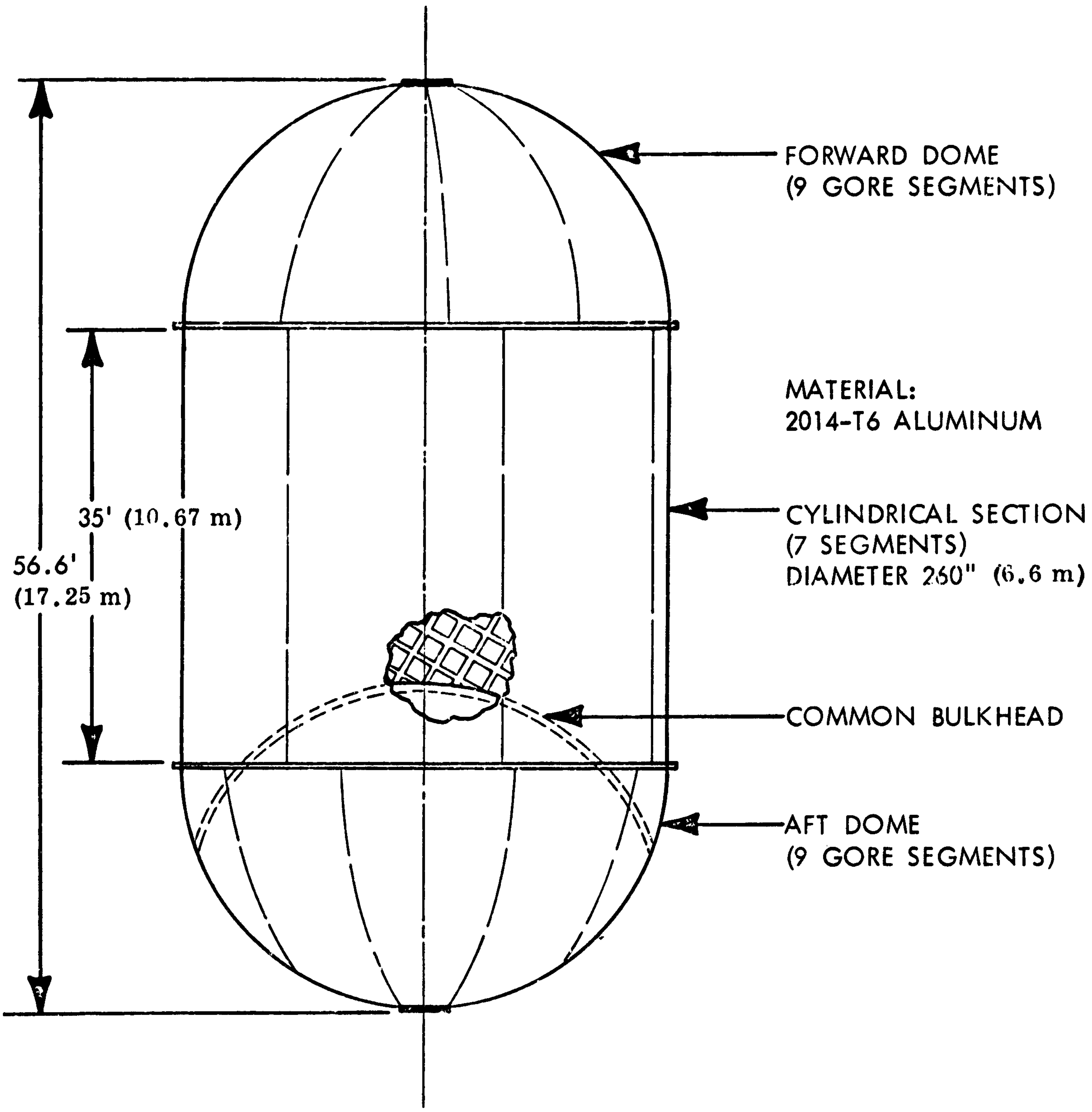


Figure 2-3. Propellant Tank Structure (Structural Element No. 2)

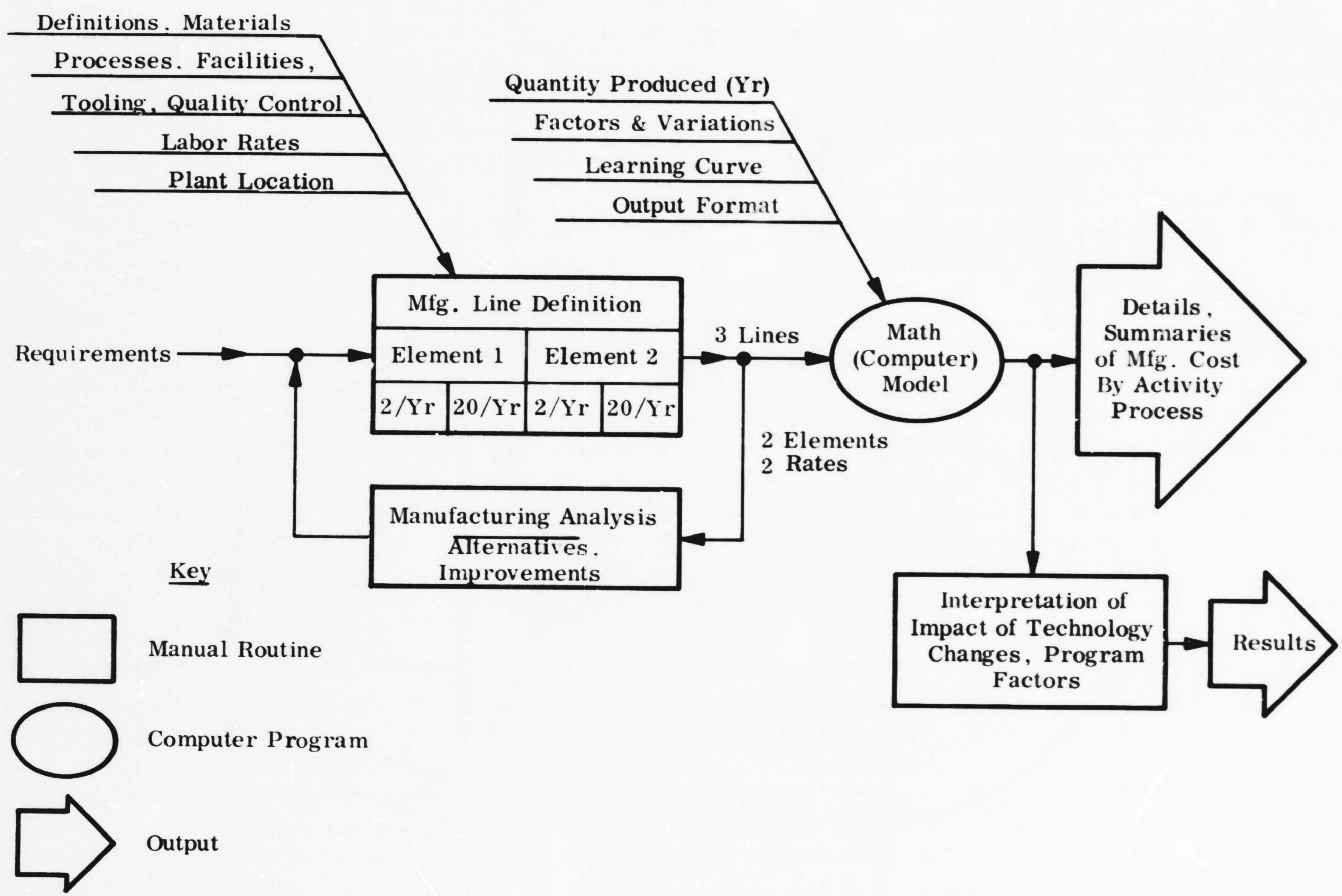


Figure 2-4. Manufacturing Model

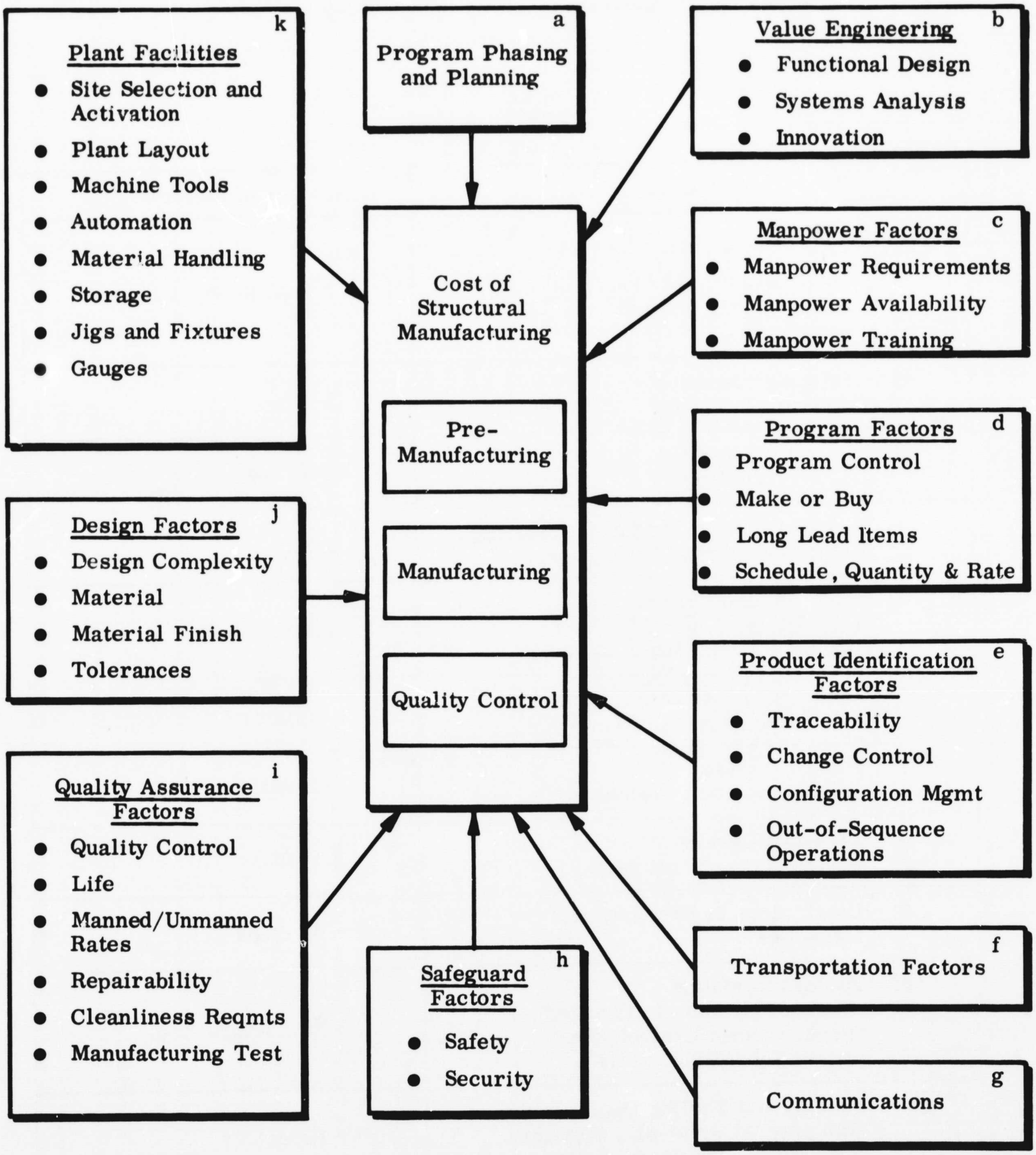


Figure 2-5. Factors Impacting Structural Manufacturing Cost

learning curves and facilities cost factors, were evaluated in a broad, parametric study. A list of the major variables is shown in Table 2-2.

Table 2-2

Study Variables

Variable	Number of Observations
1. Type of Structure (Size, Pressurized vs. Non-Pressurized, Manned vs. Unmanned)	2 Structures
2. Rate of Production (2/Year, 20/Year)	2 Rates
3. Quantity Produced (1,4,10,20,100)	Average of 3 Quantities
4. State of the Art of Mfg. Technology (Mfg. Technology Differences)	3 Lines
5. Cost Elements (Areas) (Facilities, Tooling, Pre-Manufacturing, Manufacturing)	4 Areas
6. Cost Elements (Labor Type) (Material, Mfg. QC, Total)	4 Types
7. Plant Location (Transportation, Separation)	2 Locations
8. Learning Curves (100 percent, 80 percent)	2 Values
9. Detail Steps in Fabrication, Inspection	~ 80 Steps
10. Factors Variation (Design Tolerances, Changed Specs, Change Control, Improved Scheduling, etc.)	~ 20 Factors
11. Facility and Tooling Depreciation (100 percent write-off, straight-line, sum of the years digits)	3 Rates
12. Taxes and Interest for Facilities and Tooling (None, 3 percent tax—6 percent interest)	2 Values

If all possible combinations of these factors were considered, the number of calculations required exceed one million. To keep the study within manageable bounds, the 12 basic combinations of two structures, two rates, and three lines were considered as a baseline for study evaluation. Using the computer program selected, variables were evaluated singly and in combinations to provide the necessary broad visibility into total manufacturing economics.

2.4 ASSUMPTIONS

In arriving at cost for facilities, tooling, material, labor, and processes, the assumptions shown in Table 2-3 were used.

These assumptions were developed from numerous contacts with vendors and industry; in particular, the Air Force Manufacturing Engineering Laboratory was helpful in establishing typical costs used in study calculations. Care should be exercised in use of the absolute values of cost derived in this study, since cost values vary with time and geographic location.

This study was concentrated on the aluminum alloys and their current and future manufacturing costs since they are the principal materials currently used in space vehicle structures. Future studies should be performed to evaluate the impact of advanced structural materials, such as beryllium and carbon filament composites, on manufacturing costs.

Table 2-3

Baseline Manufacturing Cost Assumptions

Materials	Costs
Aluminum Sheet	\$ .68/lb*
Adhesive for Bonding	1.00/sq. ft.*
Honeycomb (Fiberglass)	20.00/cu. ft.
Extrusions (Y Rings and Cylinder Rings)	4.00/ft.

Inspection	
X-Ray Weld	\$ 5.50/sq. ft.*
	2.00/ft.*
Sonic Inspection	5.50/sq. ft.*

Facilities & Tooling**

All costs for required facilities and tooling are included as a non-recurring expense.

Taxes, Interest, and Depreciation

Total manufacturing program costs include:

a. The amount of depreciation of tooling and facilities and assume that the tooling and facilities are sold for depreciated value at the end of the manufacturing program
b. As applicable interest on capital invested in tooling and facilities at the rate of 6% of **invested** value per year of program length.
c. As applicable, property taxes on facilities and tooling equal 3% of depreciated value per year of program length.

Fabrication	
Metal Removal	
Numerical Controlled Milling	\$ 1.50/lb.*
Chem Mill	5.50/lb.*
Tig Welding	7.00/ft.*

Labor Rate ***	
Pre-Manufacturing	\$15.00/hr.
Manufacturing (Includes All Shop Personnel)	15.00/hr.
Quality Control (Includes Manufacturing Test)	15.00/hr.

Material Constraint

All Materials in Elements 1 and 2 are Aluminum Alloys with the exception of some fasteners.

Recycle Due to Changes

A 40 percent recycle of all pre-manufacturing operations (planning, scheduling, etc.), was included to account for impact of changes. This assumes that 40 percent of all planning and manufacturing engineering work would be done over to correct for changes during the manufacturing cycle.

Land

(Various prices were assumed for land, depending on location.)

Daytona Beach Vicinity—\$12,000/Acre
Cape Kennedy Vicinity—\$14,500/Acre
Philadelphia Vicinity—\$35,000/Acre

Factory/Building Space

(Assumed prices varied depending on usage. ceiling height.)

Low Bay Ordinary Shop (30 Foot)—\$18/sq. ft.
Composite Factory and Engineering—\$25/sq. ft.
High Bay Assembly (100 Foot)—\$60/ft.

NOTES:

Cost Basis—All costs including tax rates and interest on capital invested in facilities and tooling are based on 1969 values and are shown without fee. Interest and tax rates are based upon those prevalent in Volusia and Brevard Counties, Florida (Daytona Beach/Cape Kennedy vicinity).

* —Data from Reference 1.

** —Data from Reference 2.

*** —Labor rates include direct labor charges and overhead and G&A expenses, including proportionate share of cost of operating and maintaining the buildings and tools, heat, light, water, services, consumable supplies, IR&D, documentation, etc.

SECTION 3

RESULTS

3.1 MANUFACTURING COST DISTRIBUTION

Typical cost distribution of one of the structural elements (propellant tank, Element No. 2) and three manufacturing technology lines is illustrated in Figure 3-1 for a production rate of 20 per year for 5 years. Identifying nomenclature is noted at the top and within the illustration. Baseline conditions for each of the lines are illustrated by the first bar graph of this figure.

Other bars on Figure 3-1 illustrate the impact of varying taxes, depreciation assumptions, learning curves for the 20 per year cases and other selected factors (described later). The distribution of manufacturing costs comprising the total can be seen on each of these bars and the relative magnitude of nonrecurring (bottom of bar) and recurring (top of bar) can similarly be identified. Additional details for both structural elements and manufacturing rates of 2 per year and 20 per year are given in Volume 2.

3.2 MANUFACTURING TECHNOLOGY DIFFERENCES

The cost differences between lines 1, 2, and 3 are illustrated in Table 3-1 for the 12 nominal cases. These results vary with introduction of additional variables listed in Table 2-2.

Table 3-1
Unit Manufacturing Cost—K$/Unit

		State of the Art Line No. 1 Baseline	Improved Technology Line No. 2	Advanced Technology Line No. 3
Frustum (Element No. 1)	10 Units at 2/Year	$ 109.4 (100%)	$ 116.5 (106.4%)	$ 126.1 (115.2%)
	100 Units at 20/Year	21.8 (100%)	21.1 (96.7%)	19.7 (90.3%)
Tank (Element No. 2)	10 Units at 2/Year	$1757.6 (100%)	$1453.8 (82.7%)	$1713.2 (97.4%)
	100 Units at 20/Year	673.7 (100%)	601.8 (89.3%)	580.8 (86.2%)

Line No.	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
Depreciation	100%	100%	SL	SL	SL	100%	100%	SL	SL	SL	100%	100%	SL	SL	SL
Learning Curve	100%	100%	100%	80%	80%	100%	100%	100%	80%	80%	100%	100%	100%	80%	80%
Taxes(Local)	0	3%	3%	3%	3%	0	3%	3%	3%	3%	0	3%	3%	3%	3%
Interest	0	6%	6%	6%	6%	0	6%	6%	6%	6%	0	6%	6%	6%	6%
Changes to Factors	0	0	0	0	4+5+8	0	0	0	0	4+5+8	0	0	0	0	4+5+8

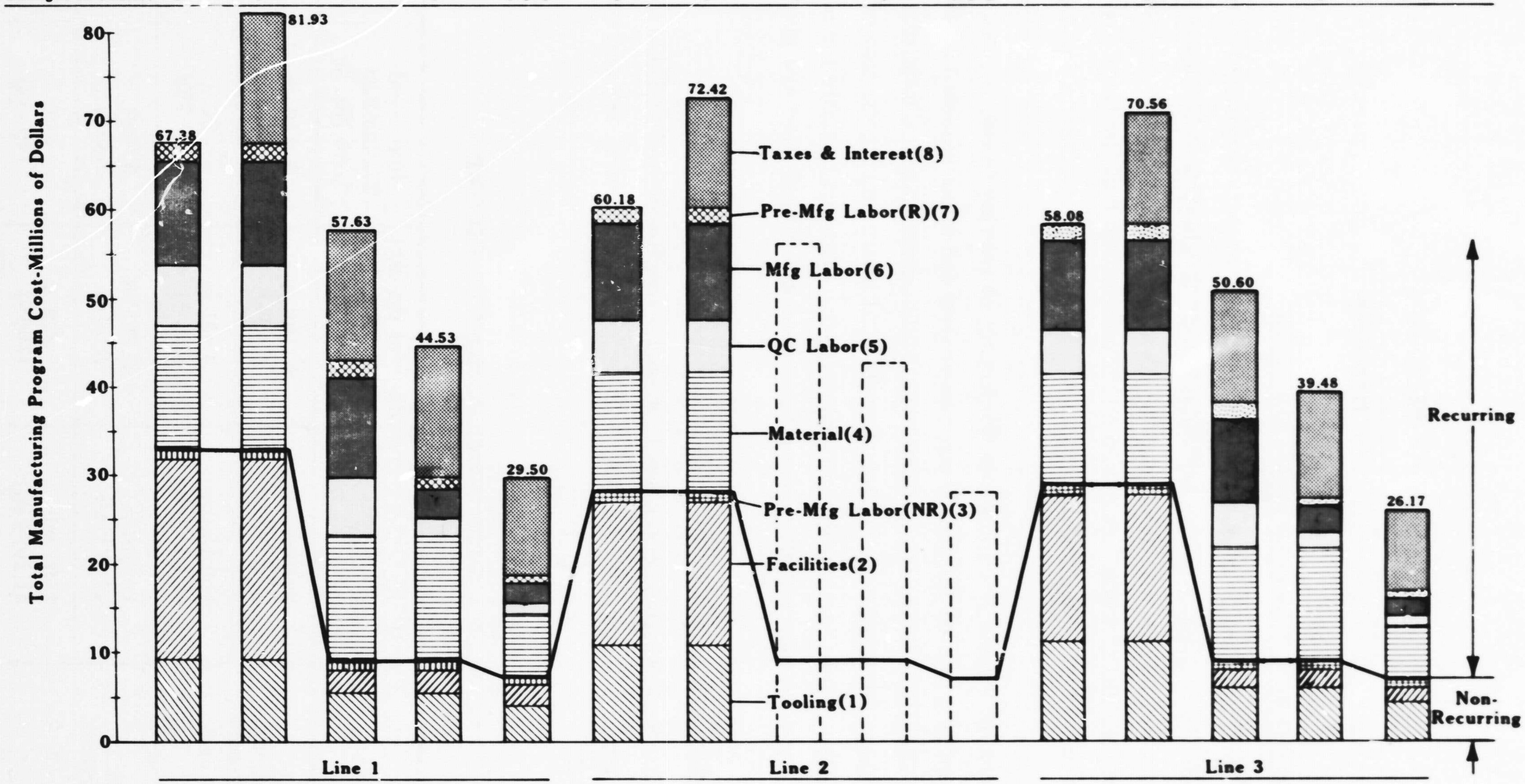


Figure 3-1. Manufacturing Cost Distribution for the Propellant Tank Structure (Element No.2) and 20/Year Production for 5 Years

Comparing advanced technology (Line 3) against state-of-the-art (Line 1), the largest variation in unit costs ranged in the worst case from a unit cost increase of 30 percent for Element No. 1 to a per unit cost decrease of nearly 20 percent for the best case with Element No. 2. But in the main, manufacturing technology improvements had only a minor influence on costs.

With the relatively low production rates of aerospace hardware programs, advances in manufacturing technologies are more likely to improve quality and reliability than reduce manufacturing cost. By applying automated machine tooling, utilizing the consolidated facilities, eliminating interplant transportation and using of new and improved processes could result in reduction of up to 60 percent in the number of major parts and elimination of up to 40 percent of the welded joints.

For both elements the recurring costs are reduced for the advanced lines but these reductions are offset by the increase in nonrecurring costs, primarily tooling. This results in unchanged or increased cost at low production rates and small savings (if any) at the higher production rates.

Improvements in quality and reliability through the application of these new technologies, while not quantifiable at this time, should be significant. For example, improvements in Element No. 2 in reduced welding would improve quality, reduce possibilities of leakage and increase payload by 325 pounds. If this payload increase were worth $1000 per pound, then the overall value would increase by 21 to 62 percent over the Line No. 1 value. See Table 3-2.

Table 3-2

Increased Value in K$ for Payload Increase Associated With Technology Improvements from Line No. 1 to Line No. 3

	Baseline Cost (Line No. 1)	Manufacturing Δ Savings	Payload Δ Worth (For $1000/lb)	Total Δ Worth
10 Units at 2/Year	$1757.6 (100%)	$ 44.4 (2.6%)	$ 325 (18.4%)	$ 369.4 (21%)
100 Units at 20/Year	$ 673.7 (100%)	$ 92.9 (13.7%)	$ 325 (48.2%)	$ 417.9 (62%)

3.3 IMPACT OF MAJOR PROGRAM FACTORS

3.3.1 SUMMARY

The range of impact of major program factors on unit cost is shown in Figure 3-2 for quantity, depreciation, taxes and interest, labor and material, and learning curve improvements. These values are included to illustrate sensitivity of costs to those factors which comprise the costs and are not in themselves intended as practical suggestions for improvement.

The values vary for each particular set of assumptions used for the cost calculations; the upper shaded areas show the range of impact of selected variables considered in this study. One assumption having a significant impact on costs is the tooling necessary to meet the manufacturing rate selected, and bars are shown for both 2 per year and 20 per year where appropriate. A 5-year program yields production capabilities of 10 and 100 for the above rates, respectively.

3.3.2 RATE OF PRODUCTION

Production rates of two and twenty major structures per year for up to five years are low when compared with the production of airplanes or automobiles; however, these production rates bracket the Saturn V and other major space hardware programs.

Production rates and program length are factors that significantly impact element cost since they are pertinent to the defining and establishment of the cost of facilities and tooling and in turn, expected property taxes, interest on capital, and the type depreciation write-off most appropriate to the program.

3.3.3 QUANTITY PRODUCED

No single factor has a greater impact on unit cost than the quantity of like elements produced. For example, with a production capability of 20 units per year, the manufacturing cost per unit for a lot of 100 is less than 7 percent of the cost of producing a a single unit. With a production rate of two units per year, the manufacturing cost of each unit for producing 10 is in the order of 15 to 36 percent of the cost of producing one element. These significant reductions in manufacturing cost are the result of non-recurring cost amortization and reduction in recurring costs resulting from improved job learning.

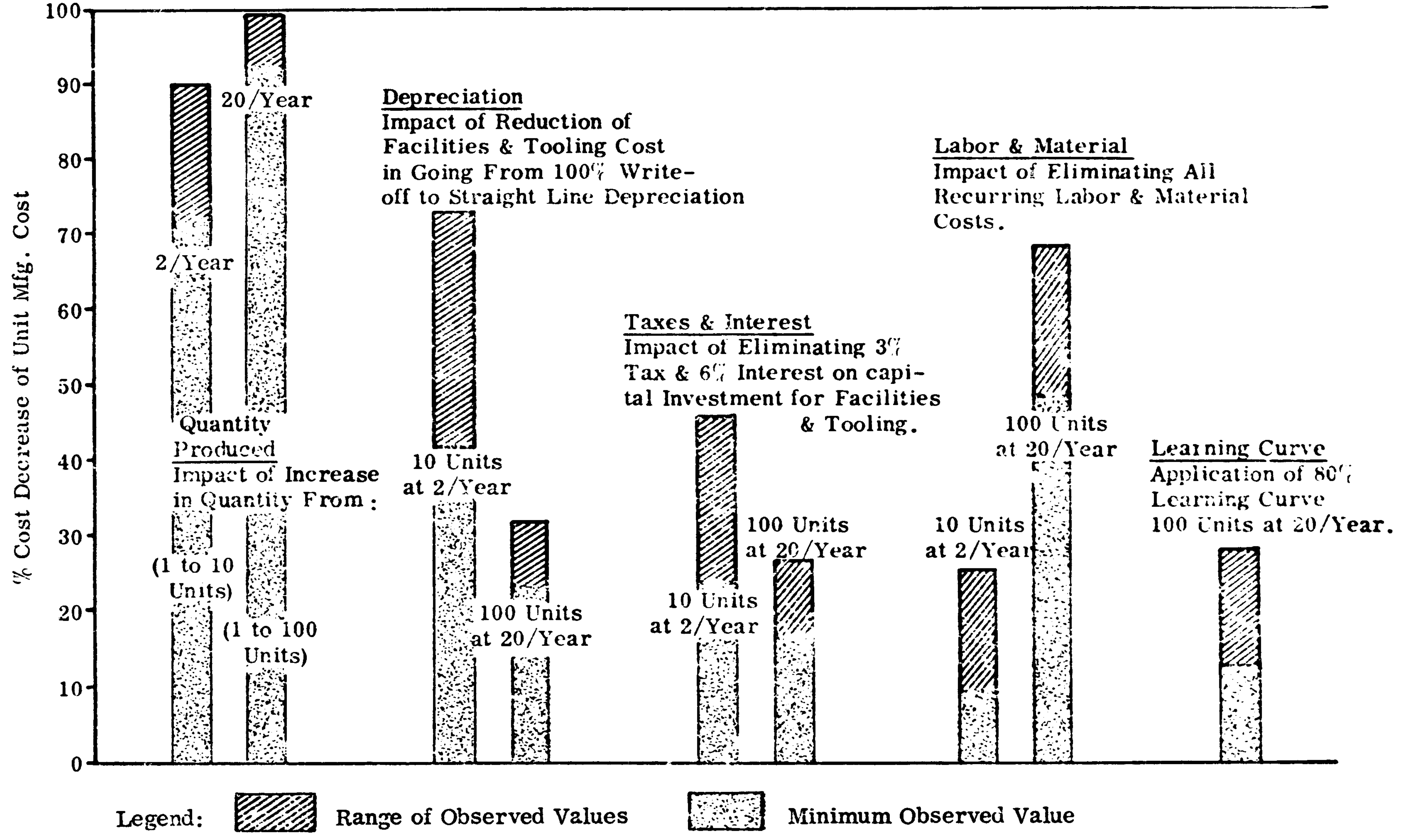


Figure 3-2. Representative Ranges of Impact of Major Factors on Unit Manufacturing Costs

Obviously, there is a strong potential for unit cost reduction in the space program where increased numbers of like elements can be produced for multi-mission purposes. The benefits primarily accrue from using existing facilities and tooling where practicable.

3.3.4 DEPRECIATION

With the predominance of fixed investment on overall costs, the rate of depreciation (recovery of capital after use) plays a major role in determining costs. For the baseline case, the fixed equipment, buildings, and tooling were written off 100 percent toward the job. This established an upper bound of costs, i.e., where costs were not recoverable for fixed capital investments. Other alternatives, such as straight-line depreciation or sum of the years digits were considered as lower limits, i.e., where costs of such capital investments can be largely recovered either through sale or use on subsequent programs. This latter use is somewhat analogous to a subcontract posture, where other contractor available facilities are used rather than the expense of investment and maintenance. The results in Figure 3-2 are considered a representative range to show the sensitivity of results to depreciation assumptions.

For low production quantities, the impact of such assumptions is the reduction of unit costs ranging from 40 percent to 72 percent; for higher production, the depreciation still has a 30 percent impact on costs.

3.3.5 TAXES AND INTEREST

Taxes and interest, even with the modest values determined for 1969 Volusia County in Florida of 3 percent and 6 percent, respectively, have a significant impact on manufacturing cost. The impact shown in Figure 3-2 ranges from a saving of 15 to 45 percent if these taxes and interest were eliminated, or 15 to 45 percent increase if the taxes and interest were doubled to 6 percent and 12 percent, respectively.

Obviously, such factors are important for aerospace manufacturing with its demands for complex facilities and tooling and low production rates.

3.3.6 LABOR AND MATERIAL

A sensitivity factor of interest is the 10 percent to 70 percent impact of recurring labor shown in Figure 3-2. For low production rates, the nonrecurring costs dominate the cost picture and even if all recurring labor and material could be eliminated, the costs would be reduced by 10 percent to 25 percent. Thus, for low production, the impact of labor rates, learning curves, material expense, or other recurring costs are less important than the capital investments and their amortization. For higher rates, the recurring costs constitute from one-half to two-thirds of the costs and are of prime significance.

3.3.7 LEARNING

The impact of learning was evaluated for the high production rate (20 per year) lines. The impact of an 80 percent Stanford Learning Curve on recurring labor costs produced reductions of from 13 percent to 28 percent.

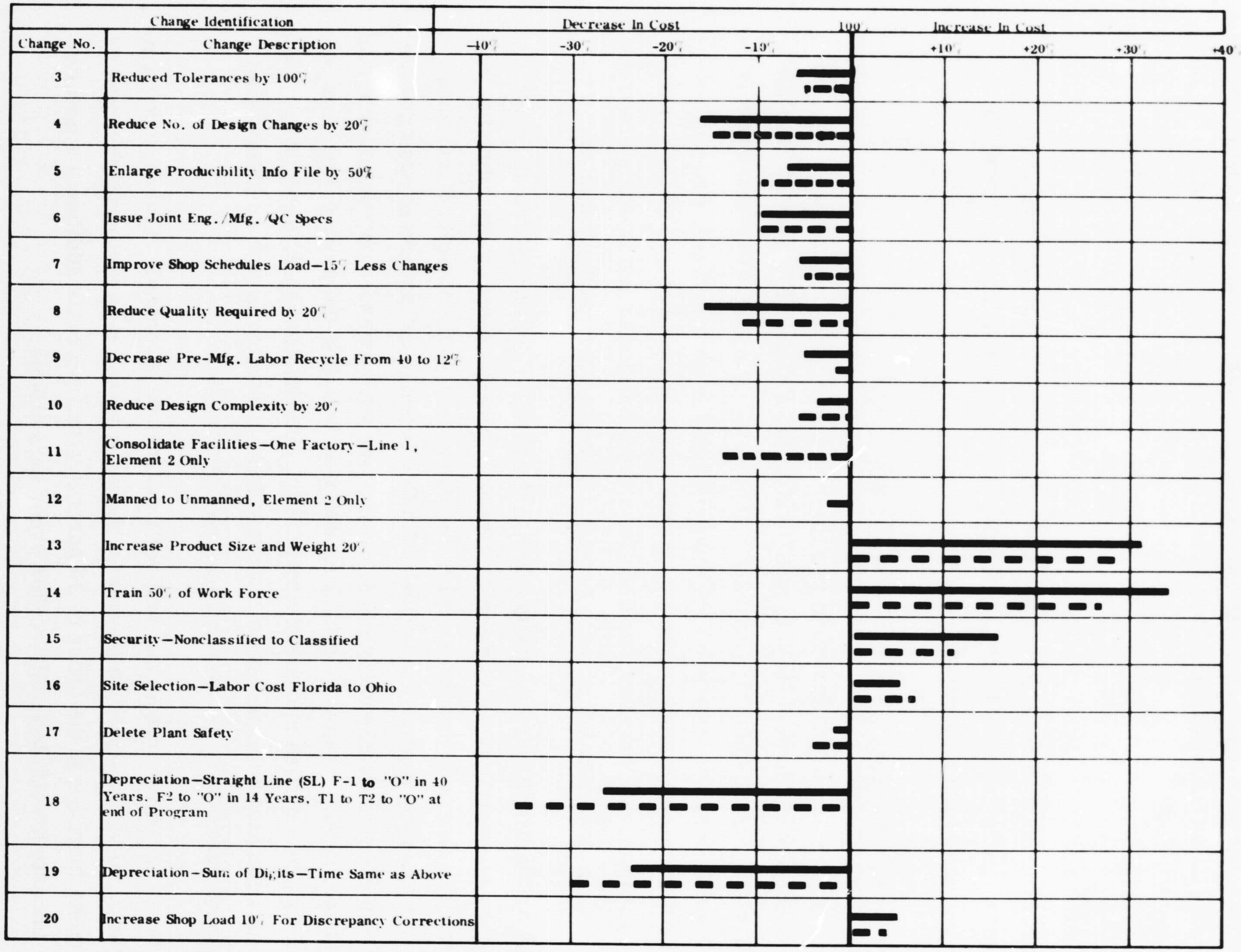
3.4 IMPACT OF OTHER MANUFACTURING FACTORS

Numerous factors, such as illustrated in Figure 2-4 were varied to evaluate their impact on manufacturing costs. Results are illustrated in Figure 3-3 against baseline conditions for the two structural elements. Significant cost reductions are noted in the areas related to design and engineering improvements, reduced quality control and plant consolidation. The impact of depreciation has been noted above. Other changes causing significant cost increases are related to additional size and training of the work force, security classification of manufactured hardware, and plant location.

Results of industrial surveys conducted during the Phase I portion of this study show that an aerospace corporation's assembly functions are frequently geographically separated from the detailed fabrication and subassembly function. Results of the study indicate that for a separation of one hundred miles between the assembly plant and detailed fabrication and subassembly plant, total costs were about 13 percent over that of a consolidated facility. Other cost factors that may increase the savings for plant consolidation include: skilled manpower availability, construction cost, local taxes, mode of transportation available, and time in transit from assembly to test or launch area. Thus, plant geographic separation is an important cost factor.

Another factor of importance is the availability of trained personnel. Training programs are very expensive. To train 50 percent of the work force, it is estimated that unit element costs increase in the order of 30 percent with a probable additional 4 percent increase in costs for limited skill worker error corrections.

Construction costs vary widely throughout the nation, construction labor costs and total construction costs have spreads of more than 30 percent from one location to another, but the net impact on total costs may be less than 10 percent.



Percentages Shown are Based Upon Line 1—Production Rate 20/Year—Program Length 5 Years.

Element No. 1 ▬▬▬▬: Base Program Cost 2183.7 K$ (100 Elements, No Taxes or Interest)

Element No. 2 ▬ ▬ ▬ ▬: Base Program Cost 67387.7 K$ (100 Elements, No Taxes or Interest)

Figure 3-3. Change Impact on Manufacturing Cost

Intangibles related to plant location include shipping mode and time in transit. Because of the size of the finished product, location near waterways or airports has a significant advantage since overland transportation has many restrictions, such as tunnel and overpass clearance, road width and load capacity. Time in transit from assembly to test or launch can be costly since the product represents invested money, and interest must be paid during transit time as well as any other time.

Additional factors are noted in Figure 3-3.

3.5 INTERACTIONS OF RESULTS

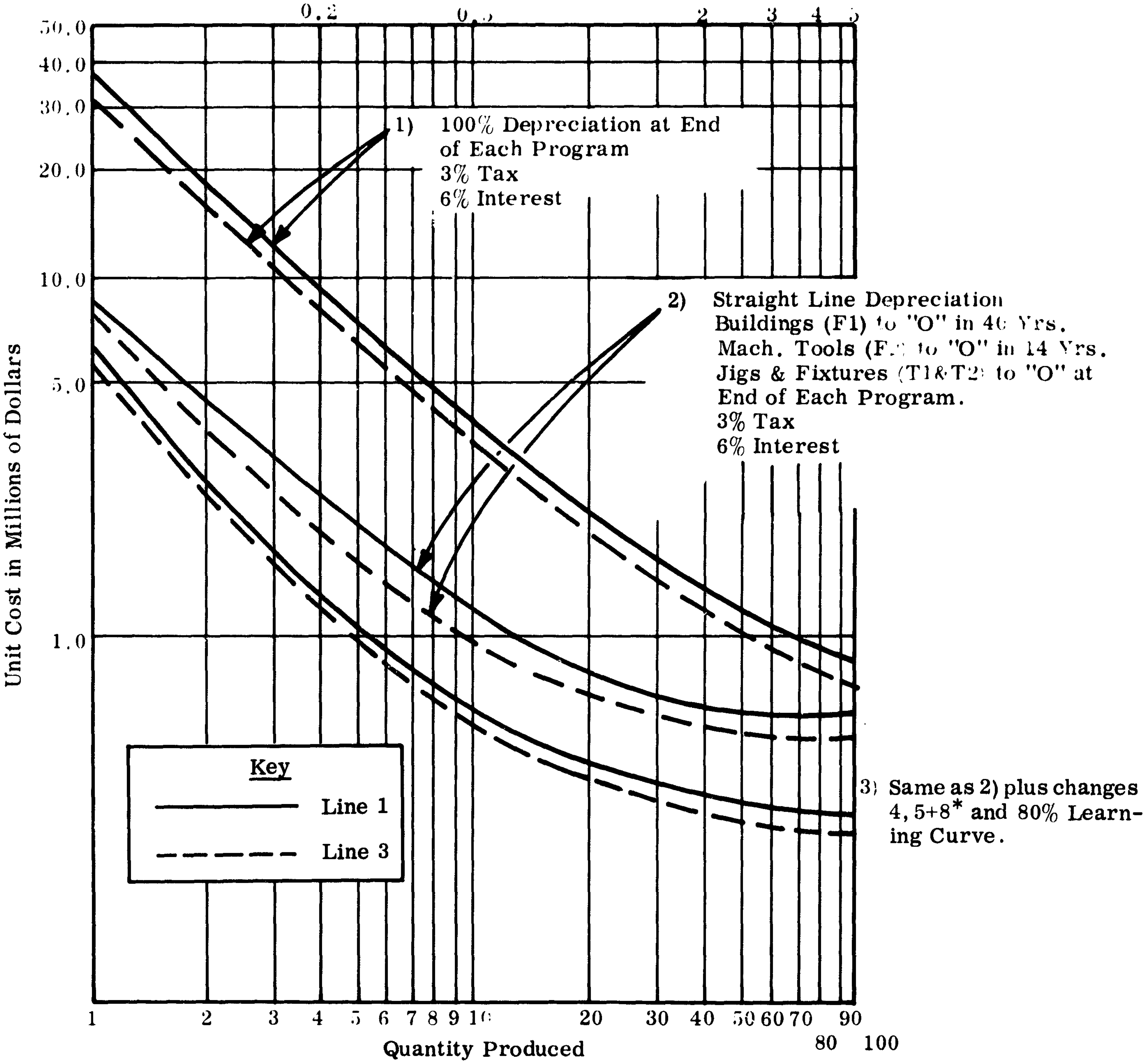
Results were evaluated for variations of several major factors simultaneously to study interaction effects. Results for Element No. 2 and production capability of 20 per year are summarized in Figure 3-4 for unit production cost versus quantity for selected variations, including:

a. Program length.
b. Type of depreciation.
c. Inclusion of tax and interest.
d. Technology improvements from Line 1 to Line 3.
e. Selected factors (4, 5, and 8) as listed in Figure 3-3.
f. Learning curve.

Similar curves for other elements and rates are included in Volume 2.

The strong impact of quantity, depreciation, and selected factors is illustrated in this figure. For low production quantity, the depreciation assumptions are important and factors (e) and (f) are of lesser importance. As quantity increases, the depreciation cost per unit drops and the impact of the other factors increases. Costs range over two orders of magnitude indicating the importance of such manufacturing considerations.

The individual calculations, including detailed discussions of interactions of some of the myriad of manufacturing factors are given in Volumes 2 and 3 of this report.



*Factors 4, 5 + 8 are discussed in Figure 3-3.

Figure 3-4. Unit Cost vs Quantity for Element 2 at a Production Rate of 20/Year

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

Quantity has the largest impact on the unit manufacturing cost of the typical aerospace structures considered in this study. Large nonrecurring costs, (including facilities depreciation) are required and must be written off against a smaller number of units produced. As quantity increases, the nonrecurring cost burden for each unit decreases. Improved learning is the secondary contributer to reduced unit cost with increased quantity.

Other factors of significant influence are: (a) methods of joining pressurized structures and (b) consolidation of facilities in which the manufacturing and assembly facilities are geographically separated. In the former case, there is a potential for cost reduction through improved welding techniques. Improvements in this area may facilitate reduction in the extensive quality control labor required with present techniques. In the latter case, a significant cost reduction can be realized by consolidating the manufacturing and assembly facilities into a single plant.

The advanced manufacturing technologies investigated show limited potential for cost reduction for the conventional aluminum materials. Advancements in manufacturing have progressed at a pace consistent with related technologies leaving only limited potential for major cost reductions; however, significant benefits of manufacturing technology advancements may be realized through improvements in quality.

In general, large (order of magnitude) cost reductions are not indicated for the conventional materials and designs at the low quantities inherent with most aerospace structural applications. The most significant area for large cost reduction, within the constraints of limited quantity, is in the potential of advanced designs which minimize nonrecurring (facilities and tooling) costs. Advanced materials, such as composite materials, may be in this category. Advanced techniques for fabrication and inspection may permit low cost facilities and hence significant cost reductions for future aerospace equipment.

Recommendations for further studies to better define technology and explore cost reductions include the following:

a. Advanced materials study to explore potential for reduced nonrecurring costs as well as improved quality and performance.

b. Evaluation of applicability of these study results to aircraft and to re-usable space vehicle structures.

c. Low-cost facilities study.

d. Welding techniques and quality control studies.

e. Use of the "MANCAN" computer program for other manufacturing applications including analysis and documentation of processes.

These studies, particularly a. and b. above, should lead to identification and exploration of new fields of technology for future lower cost vehicles.

SECTION 5

REFERENCES

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